SIM

Taking the Measure of the Universe

Space

Interferometry

Mission

December 1998

This paper provides a summary of the SIM mission. The science and technology are explored in much further detail in the book The Space Interferometry Mission: Taking the Measure of the Universe *(Stephen Unwin and Rudolph Danner, editors), scheduled for publication in March 1999.*

The Space Interferometry Mission is managed by the Jet Propulsion Laboratory, California Institute of Technology, for the National Aeronautics and Space Administration.

SIM

In 1989, the National Research Council commissioned a study to provide advice on the future direction of astronomy. In their report, entitled The Decade of Discovery, the group of experts, chaired by Professor John Bahcall, recommended the development of ground-based optical and infrared interferometers and the development of an optical interferometer in space for high-precision astrometry. Today, 10 years after this report, ground-based infrared and optical interferometers have become reality and the development of the Space Interferometry Mission is well on its way. This summary paper provides a synopsis of the SIM mission.

A Revolution in Astrometry

Astrometry, the science of measuring the positions and thus the motions of celestial objects, is among the oldest branches of astronomy. Astrometric measurements form the bedrock for determining distances to astronomical objects, and as such they are the foundation on which almost all of astronomy is based. Dramatically improved astrometric data, and the resulting modifications and improvements to the distance scale, will fundamentally improve our understanding of astrophysical phenomena both nearby and at cosmological distances.

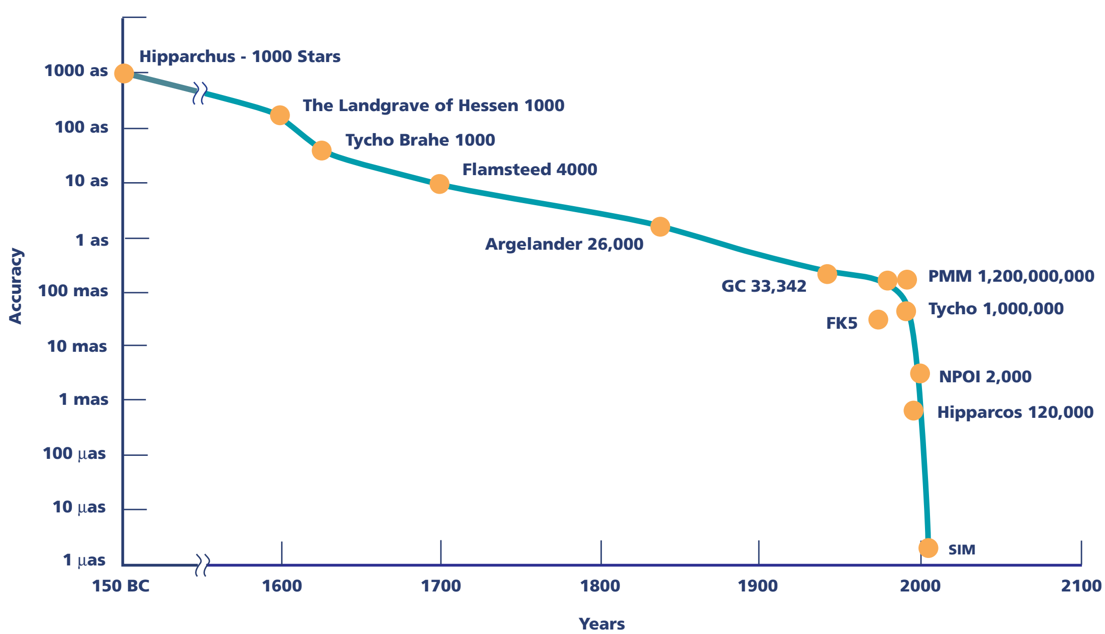
The Space Interferometry Mission (SIM) — a cornerstone mission within the National Aeronautics and Space Administration

(NASA) Origins Program — promises a better than two-orders-of-magnitude improvement in measurements of stellar positions, proper motions, and parallaxes. This is no incremental improvement in performance — it is a revolution.

The prospects for new discoveries are vast, and such an advance in performance will undoubtedly turn up many surprises. Investigations into stellar structure, composition, and evolution; the dynamical evolution of our stellar neighborhood; the density of the local interstellar medium; and the frequencies of binary stars, brown dwarfs, and planetary systems — all will benefit directly from SIM's astrometric capabilities. These fields are important to our understanding of the origin of our solar system and the development of other planetary systems. Additionally, refining the extragalactic distance scale, as well as studying the dynamics of our own and other galaxies, will yield insights into the origin and evolution of galaxies.

A Progression in Astrometric Accuracy

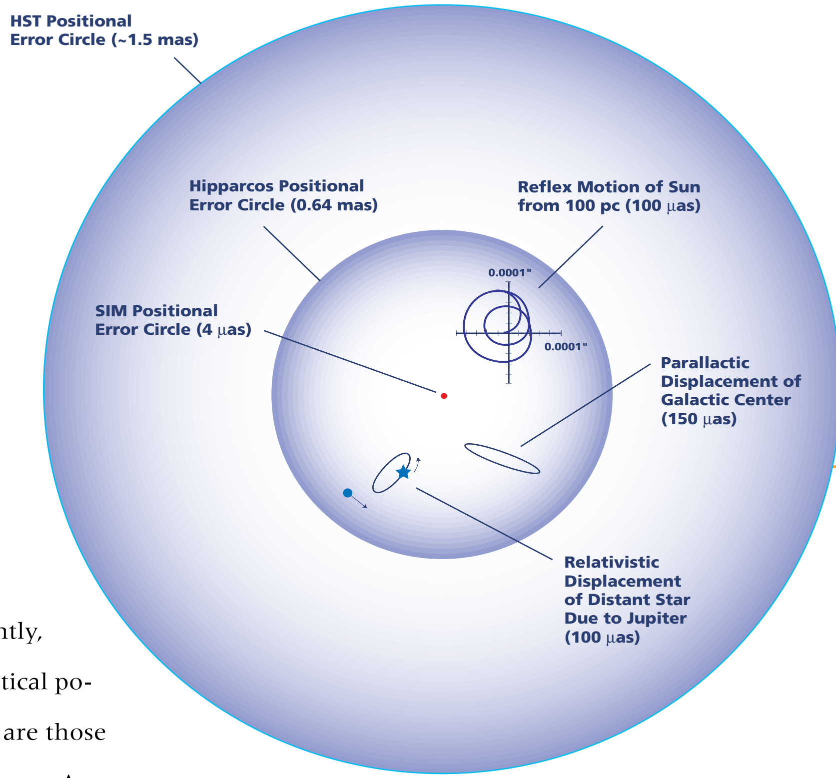
The history of astrometry begins with Hipparchus (150 BC), who measured 1,000



Astrometry (measuring position and hence motions of celestial objects) has been a pursuit of astronomers through the ages. In the last decade, ESA's Hipparcos satellite has provided a leap in astrometric accuracy. In the next decade, SIM promises yet another leap (more than two orders of magnitude) over Hipparcos.

stars at 1,000-arcsecond accuracy. Progress through the centuries was slow, but the last decade has seen a dramatic change. Currently, the most accurate optical positional observations are those from the European Space Agency (ESA) Hipparcos mission. The Hipparcos catalog contains positions at milliarcsecond accuracy for 120,000 stars as faint as 12th magnitude — a two-orders-of-magnitude improvement in astrometric accuracy relative to ground-based techniques. In the next decade, SIM promises an additional improvement over Hipparcos of better than two orders of magnitude in astrometric accuracy for stars more than three orders of magnitude fainter.

Unlike Hipparcos, a survey mission, SIM is a pointed instrument observing a relatively small number (10,000–30,000) of targets. SIM will, therefore, address a completely different set of scientific problems.



Shown are three examples of celestial motions too subtle to be detected even with the Hipparcos satellite, the current best standard for astrometry. These, and even much more subtle motions, will not escape SIM's keen vision.

A significant aspect of SIM is its ability to observe very faint objects at high levels of accuracy — 4 µas at 20th magnitude. Some of the most intriguing science requires observations of a limited number of these faint objects. Among the SIM targets will be a set of approximately 100 objects at 20th magnitude.

Tracing SIM to the Bahcall Report

The foundation of SIM science objectives is firmly rooted in the recommendations of the last Astronomy and Astrophysics Survey Committee (1991 Bahcall Report). The report noted that “Astrometry, which is concerned with the measurements of the celestial sources, ranks among the oldest and the most fundamental branches of astronomy and now is on the verge of a technological revolution.” The Bahcall Report recommended an astrometric interferometry mission as a high priority for the 1990s possessing the following attributes (excerpted from page 85 of the report):

“The mission requirement would be to measure positions of widely separated objects to a visual magnitude of 20 with a precision of 30 millionths of an arcsecond; a more challenging goal would be to measure positions with a precision of 3 millionths of an arcsecond.”

SIM’s requirement is to perform global astrometry at the level of 4 millionths of an arcsecond — which is at the most stringent end of the recommended range.

“The [mission] … would permit definite searches for planets around stars as far away as 500 light-years through the wobbles of the parent star….”

SIM’s requirement is to perform narrow-angle astrometry at the level of 1 µas, which permits detection of Jupiter-mass planets many thousands of light-years away, and planets with masses as small as a few Earths around nearby stars.

“[The mission would permit] … trigonometric determination of distances throughout the [G]alaxy….”

SIM will be able to directly measure distances via parallax to better than 10 percent anywhere in the Galaxy. Furthermore, SIM will put the cosmic distance scale on solid footing by directly calibrating the luminosity of Cepheids.

“[The mission] … would demonstrate the technology required for future [interferometry] space missions.”

SIM serves as the technological pathfinder for the future Terrestrial Planet Finder (TPF) by specifically addressing some of the most challenging technological needs of TPF (see “Beyond the Bahcall Recommended Science” in this paper).

Scientific Goals

The range of science programs that can be undertaken by SIM's astrometric capabilities is astoundingly far-reaching and varied. Here we present examples from the SIM science program to illustrate the richness of opportunity that the mission will offer. Determination of the distance scale, the search for stellar companions such as brown dwarfs and planets, and dynamics throughout the Milky Way Galaxy are but three examples of the science programs that can be pursued with this radical improvement in astrometric accuracy. A more detailed treatment can be found in The Space Interferometry Mission — Taking the Measure of the Universe, a book scheduled for publication in March 1999.

Calibrating the Distance Scale

How big is the universe? How fast is it expanding? How old is it? How is mass distributed on a large scale? The answers to these fundamental questions rely on accurate distance measurements to galaxies far enough away to be participating in the general Hubble expansion. These measurements, in turn, depend on accurate calibrations of objects that serve as "standard candles" in those galaxies. Currently, these calibrations are known to at best 10 percent. Differences in interpreting cosmological models with very different implications for the long-term fate of the universe reside in that 10-percent uncertainty.

Distances to Galactic Cepheids represent the first step of the extragalactic distance scale. Uncertainties here propagate outward. Improving this uncertainty from the current 10 percent to less than 1 percent will improve the accuracy of all subsequent steps in the extragalactic distance scale and will provide the foundation and motivation for further improvement of those techniques.

SIM will determine distances of hundreds of Galactic Cepheids up to 4 kpc away, improving the Cepheid scale to better than 1 percent. This yields a Cepheid period–absolute magnitude diagram that is no longer limited by distance uncertainties.

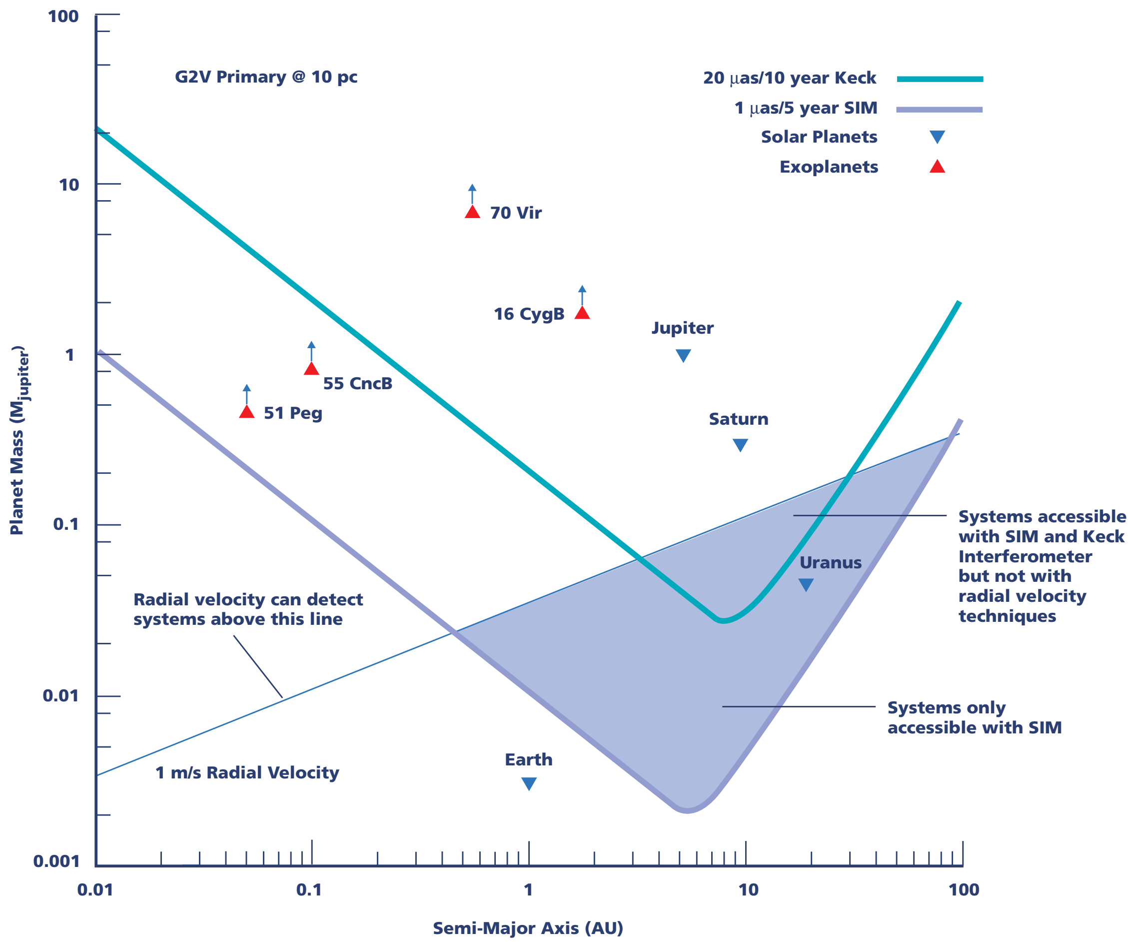
Because accurate near-infrared photometry minimizes the effects of extinction, astronomers will make great progress in correcting the period–absolute magnitude relation for parameters such as metallicity. The result will be greatly improved calibrators for determining the distances to other galaxies.

Planet Detection

Confirming the existence of worlds other than Earth has long been an unattained "holy grail" of astronomy. For centuries, philosophers and religious thinkers have debated the uniqueness of Earth and have pondered the existence of other worlds. But as late as only a few years ago, none had been definitely found.

Now, with confirmed discoveries of Jupiter-mass companions in hand, astronomers have entered a new era in the quest, when questions no longer deal with the possible existence of planets but rather with frequency, process of formation, and potential for harboring life. SIM will be the first in a sequence of space instruments to study extrasolar planets, and the single most important step in the next decade towards understanding planetary systems in their generality and investigating the habitability of worlds other than Earth.

The defining capability of SIM in the search for extrasolar planets will be its ability to measure with unprecedented accuracy the movements of stars, and to follow those movements for the duration of its five-year mission. SIM's narrow-angle astrometry mode will measure differential positions between stars in a ~1-degree region with 1-μas accuracy. This will allow SIM to detect planets in the range of 2 to 20 Earth masses around a large sample of nearby stars, and will detect more-massive planets around stars many thousands of light-years away.



These measurements will provide crucial insights about the mechanisms of planet formation. For example, it is thought that in some protoplanetary disks, the disk gas dissipates before collisional accumulation can produce planetary embryos with sufficient mass to accrete disk gas. In such systems we might expect to find a number of Uranus-mass and Neptune-mass planets, but no giant planets. These "large terrestrial planets" might orbit at relatively small distances from their stars, either due to in situ formation at 1 AU, or due to inward orbital migration to even smaller distances. By detecting 2 to 20 Earth-mass planets, SIM will provide a test of whether or not planet formation occurs elsewhere by the two-step process often thought to account for the formation of Jupiter and Saturn.

Up to now, nearly all extrasolar planets have been detected using the radial velocity technique, which favors very large planets close to the parent star. SIM's astrometric capability will allow detection of planets with masses approaching that of Earth, which are better candidates for biological activities compared with the gas giants currently being detected.

Dynamics of the Milky Way

NASA's Origins Program seeks to probe the formation of galaxies, both by examining nascent galaxies and by tracing the structure and evolution of older galaxies, such as our own. Astronomers still do not fully understand the mass distribution and the dynamics of our own galaxy. Comparing the observed rotational speed of the stellar disk with the amount of mass traced by stars, gas, and dust indicates that there is a vast amount of unseen, or dark, matter. Tracing the distribution of the Galaxy's mass becomes difficult at galactocentric distances beyond the Sun's orbit, where the Galactic rotation curve is not well defined because of poorly known distances to the stars that are being used to probe the Galactic gravitational potential.

SIM will address these and other fundamental questions in the Galactic structure:

- What is the size of the Galaxy?
- What is the distribution of mass in our galaxy — both visible and dark matter?
- What are the kinematics of stars in the outer halo as well as in and near the Galactic plane?

Answering these questions will reveal much about the nature of the dark matter and the formation history of the Galaxy.

Measuring the size of the Galaxy, mapping its rate of rotation, and determining how mass is distributed among its components are interrelated and classical problems. These problems are complicated by the need to determine the deviations from pure circular rotation associated with the recently discovered central bar, and the amount and distribution of dark, as well as visible, matter.

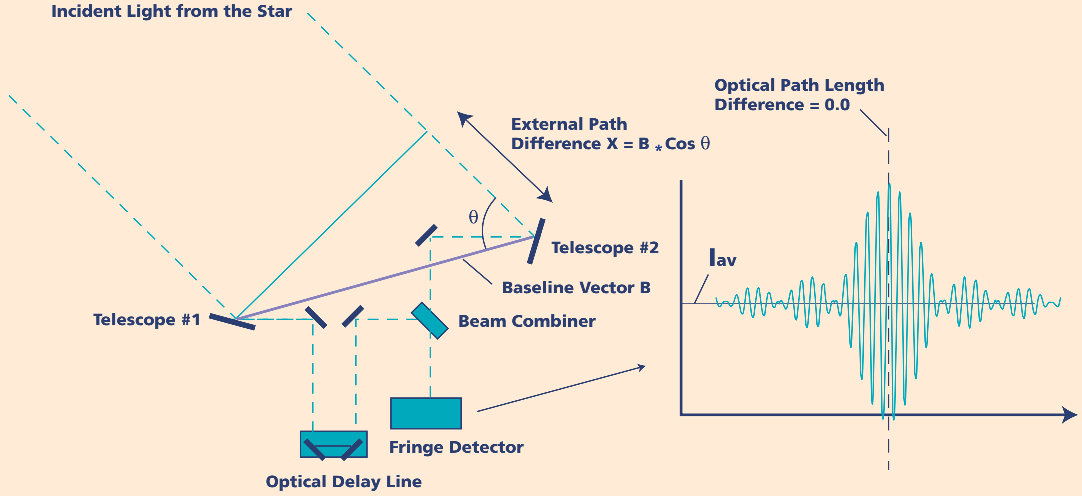
Over the lifetime of the SIM mission, the proper motions of stars in our galaxy can be determined to previously unreachable levels — at a distance of 10 kpc, transverse velocities can be measured to 1 km/sec. Thus, SIM can measure the velocities and positions of stars throughout the Galactic disk (except for regions obscured by dust) and in most of the inner Galactic halo, and will address many important problems in galactic dynamics via accurate astrometry.

How Does SIM Perform Astrometry?

Astrometry, one of the oldest branches of astronomy, is the science of measuring position and motions of celestial objects. The illustration below shows how this is accomplished using a Michelson interferometer like SIM. Two telescopes are separated by a distance, B, called the baseline. The light from a distant object arrives at one of the telescopes sooner than at the other, creating an external path difference, X. The sought-after angle θ is the angle between baseline vector B and the vector pointing to the stellar object. If one knows vector B and can determine X, then one can solve for θ and thus determine the position of the star.

How is it done? We determine the external path delay by introducing in the short arm of the interferometer an internal optical delay line, which is exquisitely and dynamically adjusted so that the light from each telescope arrives at a beam combiner at the same time. A detector at the output of the beam combiner measures the resultant signal. When the internal and external delays are not nearly equal, the detector measures an average intensity, I_{av}. As the internal delay begins to match the external delay, an interference pattern, called a fringe, emerges. Using an algorithm that senses the fringe and feeds back to the delay line, the delay line is adjusted until the fringe peaks, indicating an exact match between the internal and external delays. A metrology system measures the internal delay, and thereby determines the external path delay. Combining this with the knowledge of the baseline, one can derive the angle θ.

Sounds simple? In concept, it is. However, the challenge is to keep the interferometer stable enough so that optical pathlengths can be controlled to 10 nm or less — where a nanometer is 10 times the diameter of a hydrogen atom! Additionally, optical pathlengths must be measured to subnanometer levels. For more details on SIM's technological challenges and how they are being mastered, see the section on technology in this paper.



Much More Science

While we have touched here on only three science applications, SIM will contribute to the cutting edge of astronomy research from the largest to the smallest astronomical scales. Indeed, 21st-century astrophysics will be built on the foundation of astrometric knowledge returned by SIM. A few other areas of research that SIM is expected to impact include:

A significant aspect of SIM is its ability to observe very faint objects at high levels of accuracy — 4 μas at 20th magnitude.

Ages of Globular Clusters. Stellar-evolution models can be used to measure the age of stellar populations in globular clusters, but a major uncertainty in that age determination is the stellar luminosity. This uncertainty can be significantly diminished with accurate distance measurements from SIM.

Masses and Evolution of Close Binary Stars. Knowledge of the masses of stars in close binaries is essential to proper understanding of the physical processes, such as mass transfer, taking place. By using astrometry to measure orbits, SIM eliminates the "sin i" term, which prevents radial velocity measurements from yielding masses directly.

Tidal Tails. Tidal tails resulting from interaction with Milky Way satellite galaxies provide an excellent probe of the Galactic halo and the early history of the Galaxy. SIM's sensitivity allows study of the proper motion of the faint stars in these tails.

Rotational Parallaxes of Nearby Spiral Galaxies. Distances to nearby spiral galaxies can be measured completely independently of the standard "distance ladder" by measuring the proper motion of stars in the disk. These distances serve to calibrate the Tully-Fisher relation used to measure distances to spiral galaxies, and they also provide a direct way of calibrating the Cepheids in galaxies other than our own.

Dynamics of the Local Universe. SIM will map out, in three dimensions, the positions and motions of galaxies of the Local Group. Such data currently do not exist, but are essential for correcting models of formation and evolution of galaxy groups on the scale of a few megaparsecs.

Microlensing. SIM will detect the astrophysics signature of microlensing events from sources in the Large Magellanic Cloud, the Small Magellanic Cloud, and the Galactic bulge, and will yield lens masses directly.

SIM

Beyond the Bahcall Recommended Science

The Bahcall Report (The Decade of Discovery) of the last decadal survey, referring to its recommended astrometric interferometry mission, noted that "[The mission] …would demonstrate technology required for future space [interferometry] missions." In March 1996, NASA held a review to select between two competing architectures to ensure that the design selected for SIM would indeed pave the technological path toward future interferometers, including the Terrestrial Planet Finder (TPF). The architecture selected from that review is the basis of various designs being considered for SIM.

Many of the technologies needed to accomplish SIM's astrometric science — such as nanometer-level optical pathlength control, space-rated picometer laser metrology, and autonomous operation of space-based interferometers — are also needed for TPF. But over and above these technologies, which are needed for SIM astrometric science, SIM will also demonstrate synthesis imaging and starlight nulling to further fulfill its role as the precursor to TPF.

Synthesis Imaging

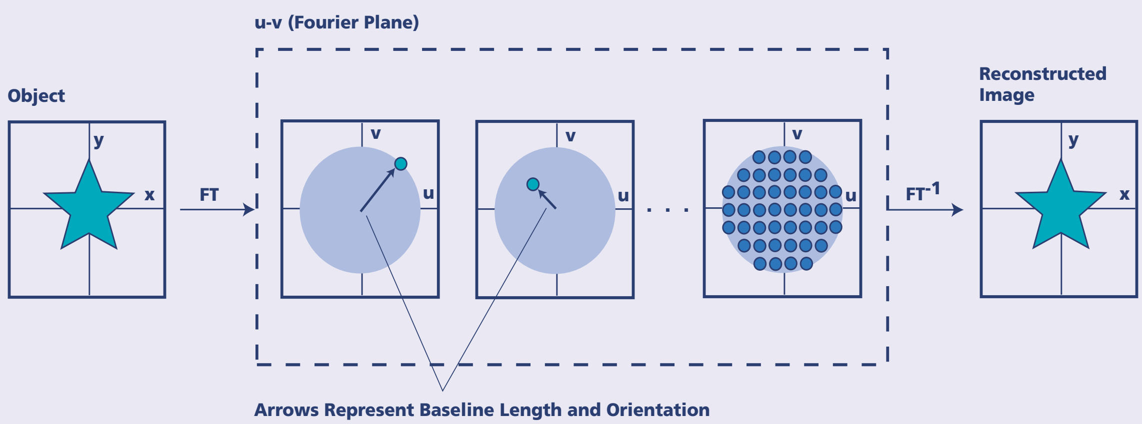
NASA's long-term goal of imaging Earth-like planets around nearby stars will not be achieved with conventional telescopes; it will require synthesis imaging with very large interferometer arrays in space. The SIM synthesis imaging capability will provide us with an early opportunity to gain vital experience with these techniques. Although SIM's basic design is driven by the astrometric science, SIM can also provide a unique capability for high-resolution imaging at 10 mas — four times higher resolution than that of the Hubble Space Telescope, albeit with a smaller field of view. While it is a *requirement* of SIM to demonstrate synthesis imaging technology by imaging such targets as globular clusters, it is a *goal* of the project to achieve full u-v coverage (subject to fiscal constraints) to allow imaging of more diverse targets such as young stellar objects, protoplanetary disks, and black holes in the nuclear regions of active galaxies.

Imaging with an Interferometer

An important aspect of any interferometer is the ability to get finer resolution by increasing its baseline. In telescopes, angular resolution is proportional to λ/D, with D being the diameter of the primary mirror. Increasing the resolution is expensive because it can be achieved only at cost of larger apertures. In contrast, the angular resolution of interferometers is proportional to λ/B, where B is the baseline — and B can be much more economically increased than D to obtain very high angular resolution. However, this high resolution is achieved over a small field of view. Unlike telescopes, where the field of view is set by the size of the detector array, in a Michelson interferometer, the field of view is limited by λ/d, where d is the diameter of the telescopes at each end of the interferometer. Assuming a 10-m baseline, SIM, operating at 0.5 µm with 30-cm telescopes, has angular resolution of 10 mas over a field of view of 0.3 arcsec.

Unlike telescopes, which image objects directly, interferometers measure the Fourier transform of the object, which is then inverted to obtain the image. The data for the Fourier transform plane (the u-v plane) is built up one point at a time — hence the term synthesis imaging.

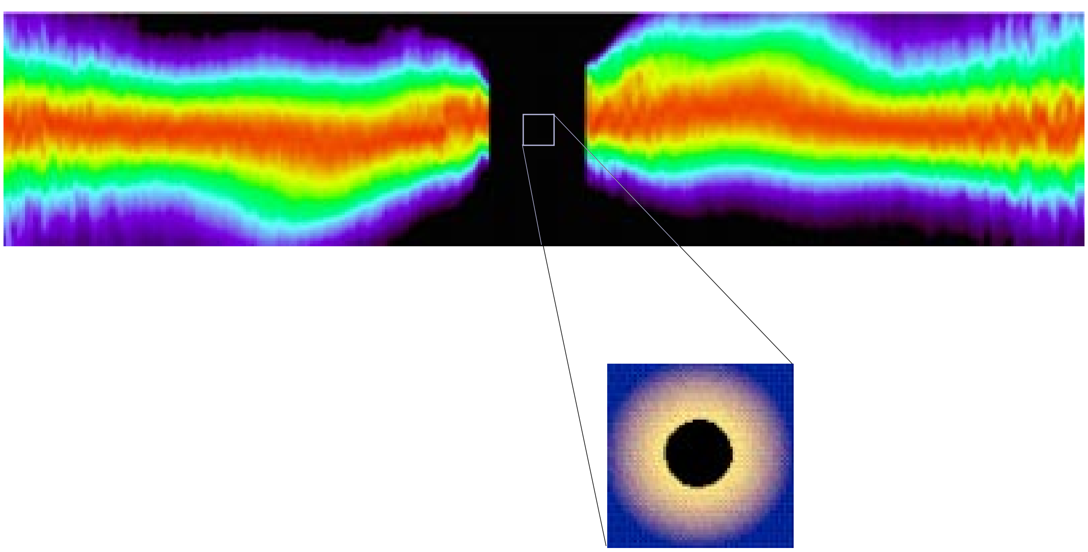
For each baseline orientation, one measures the fringe amplitude and phase, which represent a Fourier coefficient in the u-v plane. Rotating the interferometer and varying the baseline length results in filling the u-v plane. Varying the baseline requires either mechanically shrinking and expanding the baseline, or, alternately, having multiple pairwise-selectable telescopes on the baseline structure — giving in effect multiple interferometers of various baselines. The number of required points in the u-v plane varies depending on the object's complexity. With SIM, imaging an object using this technique will take several hours.



Starlight Nulling

Nulling interferometry is a special application wherein the on-axis light from a star is canceled almost perfectly, so that the star's brilliance does not wash out the glimmer of a faint object being detected off-axis. The technique essentially serves the same function as does a coronagraph, but with greatly enhanced performance. With an appropriate choice of parameters, starlight can be suppressed by a factor of ~10^{-6}, while a mere 0.1 arcsec away, light is unattenuated.

Searching for planets is an intriguing and obvious application for nulling. TPF will require rejection of 10-µm starlight at the level of 10^{-5} to 10^{-6} to ensure detection of Earth-like planets. SIM will demonstrate 10^{-4} starlight nulling at visible wavelengths (0.7 µm), which is equivalent to the TPF requirement at 10 µm.



To see dim planets or the disk structure near a bright star, the starlight must be blocked. The HST/STIS was used to mask the star Beta Pictoris (top), but the mask also covered the nearby region of interest up to 16 AU (equivalent to the orbit of Uranus). In comparison (bottom), SIM can null the starlight, yet leave exposed objects as close to the star as 1 AU, where possible planets would show themselves by "sweeping" up the dust in the "inner" planetary system.

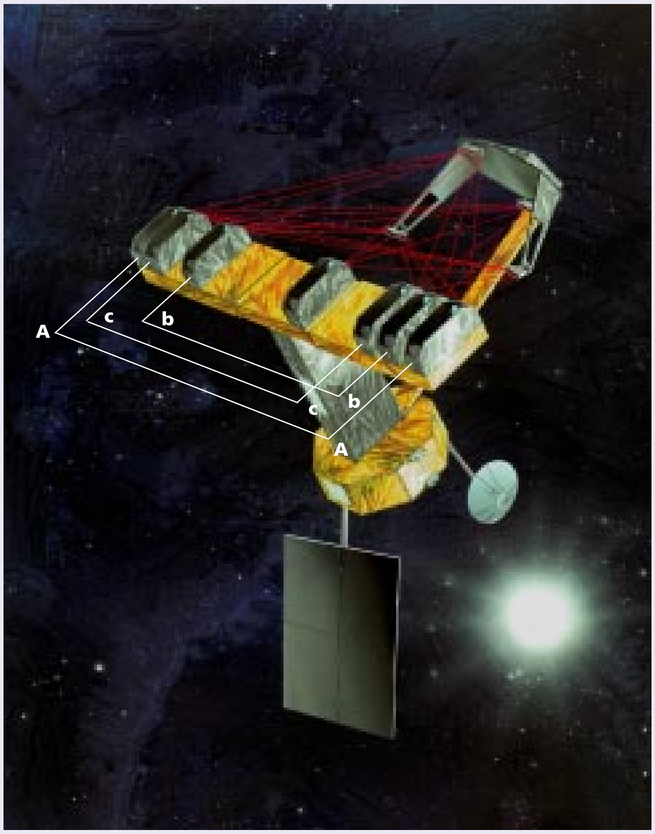
Two Implementation Concepts

Two implementation concepts are currently under study for SIM. Within the SIM team, these two concepts have come to be known as “SIM Classic” (or simply the Classic) and the “Son of SIM” (SOS). While the two concepts require many common technologies, each concept also presents a set of unique technological challenges with the promise to reduce implementation and/or operational difficulties and risks in different areas. The choice between the two will be made before fall 1999, based on the results and progress of the technology development program and cost/complexity design trades.

The Classic. In this concept, seven telescopes are spaced out over the 10-meter baseline structure. For imaging, the seven telescopes taken pairwise form 21 different baselines ranging from 0.5 m to 10 m. As the interferometer rotates to perform synthesis imaging, these various baselines — selected one at a time — nicely fill the u-v plane, resulting in high-fidelity imaging.

The Classic uses three interferometers: one science interferometer and two guide interferometers. Each of the three uses different pairs of telescopes. The telescopes at the extreme ends (A-A) are paired to form a 10-m-baseline science interferometer and the b-b and c-c pairs form the two guide interferometers. Both the Classic and SOS designs require guide interferometers, for two reasons. First, to determine the attitude of the baseline in the celestial coordinate system, SIM needs ultraprecise star trackers (microarcsecond level). Since such star trackers do not exist, SIM uses guide interferometers to serve that function. The second reason has to do with acquisition of dim targets. Because SIM requires acquisition of very dim science targets (down to magnitude 20), the science interferometer needs help in pointing its optics toward the dim star and setting its delay line to obtain fringes. This help is provided by the two guide interferometers, which can point and acquire fringes on bright targets with no other help except that provided by the spacecraft attitude-control system. The SIM computer uses the information provided from the guide interferometers to help the

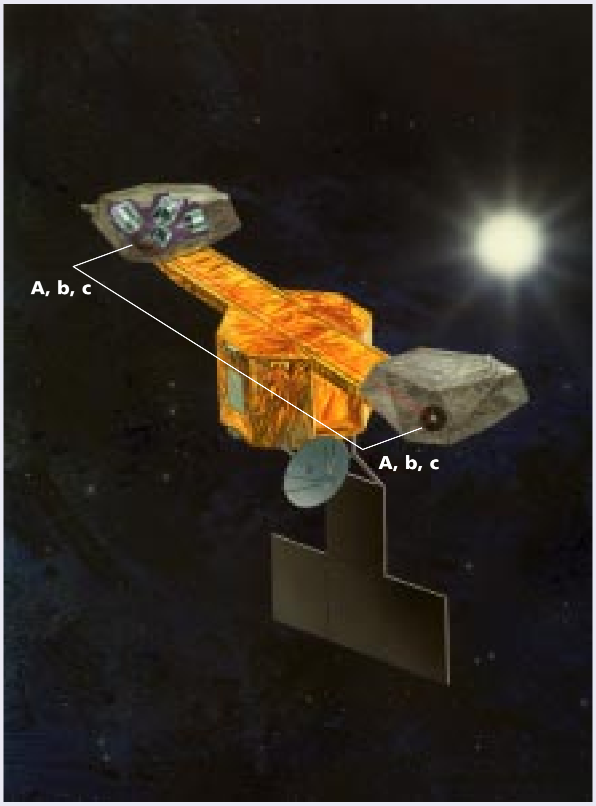
SIM Classic



science interferometer point its optics and set its delay lines (these are called angle feed forward and pathlength feed forward, respectively). However, to perform this function, at any given time the computer needs to know, with extremely high precision, the orientation of the three interferometer baselines relative to each other. The baseline of each interferometer is defined by a pair of optical fiducials — ultraprecise corner cubes. On the Classic, a multibeam external metrology system interrogates each of the corner cubes to determine the relative orientation of the three baselines.

Son of SIM. In the interest of eliminating the elaborate external metrology system, SOS creates the same baseline for all three interferometers. This is done by grouping telescopes at each end of the baseline. Telescopes grouped within a cluster point through a common optical fiducial. The external metrology is now simplified to a single-beam laser system measuring the relative distance of the two optical fiducials (corner cubes located with each cluster) to measure the baseline.

While the external metrology in SOS becomes simpler, the pointing system for each telescope becomes more complicated (precise pointing accuracy is needed to avoid metrology errors). Imaging also becomes somewhat more complicated. To create the baselines of various lengths (accomplished in the Classic case by simply distributing rather than clustering its telescopes), the SOS needs to mechanically move the clusters of telescopes at each end closer to and further from one other.



Son of SIM (SOS)

Both SIM concepts are capable of the same performance in narrow-angle and wide-angle astrometry, imaging, and starlight nulling. While both require many common technologies, each poses unique technological challenges with the promise of reduced development and operational difficulties in different areas. A choice between the concepts will be made by fall 1999.

SIM

A Community of Science Participants

We have highlighted the importance of the SIM science program, but what are the opportunities for the astronomical community at large? SIM will involve a broad community of researchers, most of whom may not consider themselves interested in astrometry per se, but who will rely on precision astrometry as a powerful tool in their astronomical research.

Given the ever-increasing need for higher resolution, interferometers will become observatories of choice that many scientists will seek out in the coming decades.

A Science Working Group, serving as representatives of the scientific community, has defined a number of key scientific questions that SIM should address, and from which, in turn, the project has defined instrument specifications. A SIM Science Team to replace the current Science Working Group will be selected competitively through a NASA Research Announcement (NRA), targeted for release by mid-1999. Some Science Team members will propose and will be selected for individual research projects; others will become leaders of teams conducting Key Projects — campaigns to answer the most important scientific questions and those that use the largest portions of the SIM resources. Once selected, Science Team members will be expected to work closely with the SIM project prior to launch to ensure that the mission meets its scientific goals.

In addition to the allocations to the Science Team, a significant fraction of the available time will be devoted to a Guest Observer program, with awards made shortly before the SIM launch. As a pointed instrument, SIM will have the ability to respond to "target of opportunity" observations such as supernovae, and the observing schedule will be kept flexible enough to provide this important function. A second Guest Observer solicitation is planned for early in the mission after launch.

SIM is a targeted instrument with a relatively short list of targets. Effective scientific use of SIM depends on the careful selection and characterization of targets to the greatest extent possible prior to launch.

For the science community, this means that NASA recognizes the need to support the task of target selection, including supporting observations where necessary, well before launch. The first such task — astrophysical criteria for stars to be used in the SIM astrometric reference grid — was the target of a NRA released in summer 1998, leading to selection of a number of proposals in fall 1998. (Approximately 5,000 stars will be selected as a SIM reference grid. Positions of other target stars to be studied will be referenced to this grid.) A second NRA for further grid studies will be released in early 1999. More NRAs are planned, and as the grid issues are resolved, the emphasis will change to other preparatory science. While SIM is expected to be launched in 2005, now is the right time for astronomers to be considering important projects and associated target lists.

Michelson Fellowship Program

In recent years, large telescopes on the ground (Keck) and in space (Hubble) have produced spectacular results, engaging many in the astronomical community and the public. In comparison, optical and infrared interferometers are novel, and as observational tools they are unfamiliar to most in the astronomical community. While the concept of interferometry has been around for many decades since first introduced by Michelson, up until now it has been mainly the domain of radio astronomers. The dawn of optical interferometry as a practical tool is upon us, however. Given the ever-increasing need for higher resolution, interferometers will become observatories of choice that many scientists will seek out in the coming decades.

To assist the science community and encourage the next generation of astrophysicists to become more familiar with interferometry, the SIM project has established the Michelson Fellowship Program. This program will be used to fund a few fellowships for graduate work relating to interferometry, post-doctoral research, and a distinguished lecture series. Additionally, in situ summer schools will be held at ground interferometry facilities in Arizona and California to familiarize participants with interferometry as a science tool (120 people attended the first such summer school in 1998). More information about these opportunities will be available soon on the SIM Web page at <http://sim.jpl.nasa.gov>.

SIM

Technology Development

An optical interferometer in space presents formidable technological challenges, yet most aspects of SIM technology have been in development throughout the current decade. These include experimental ground interferometers of various capabilities, disturbance control of flexible structures for space interferometer baselines, development of active optics and laser metrology, and real-time control software for interferometer operations. The pace of technology development picked up considerably in 1998 when the project entered its formulation phase.

Requirements

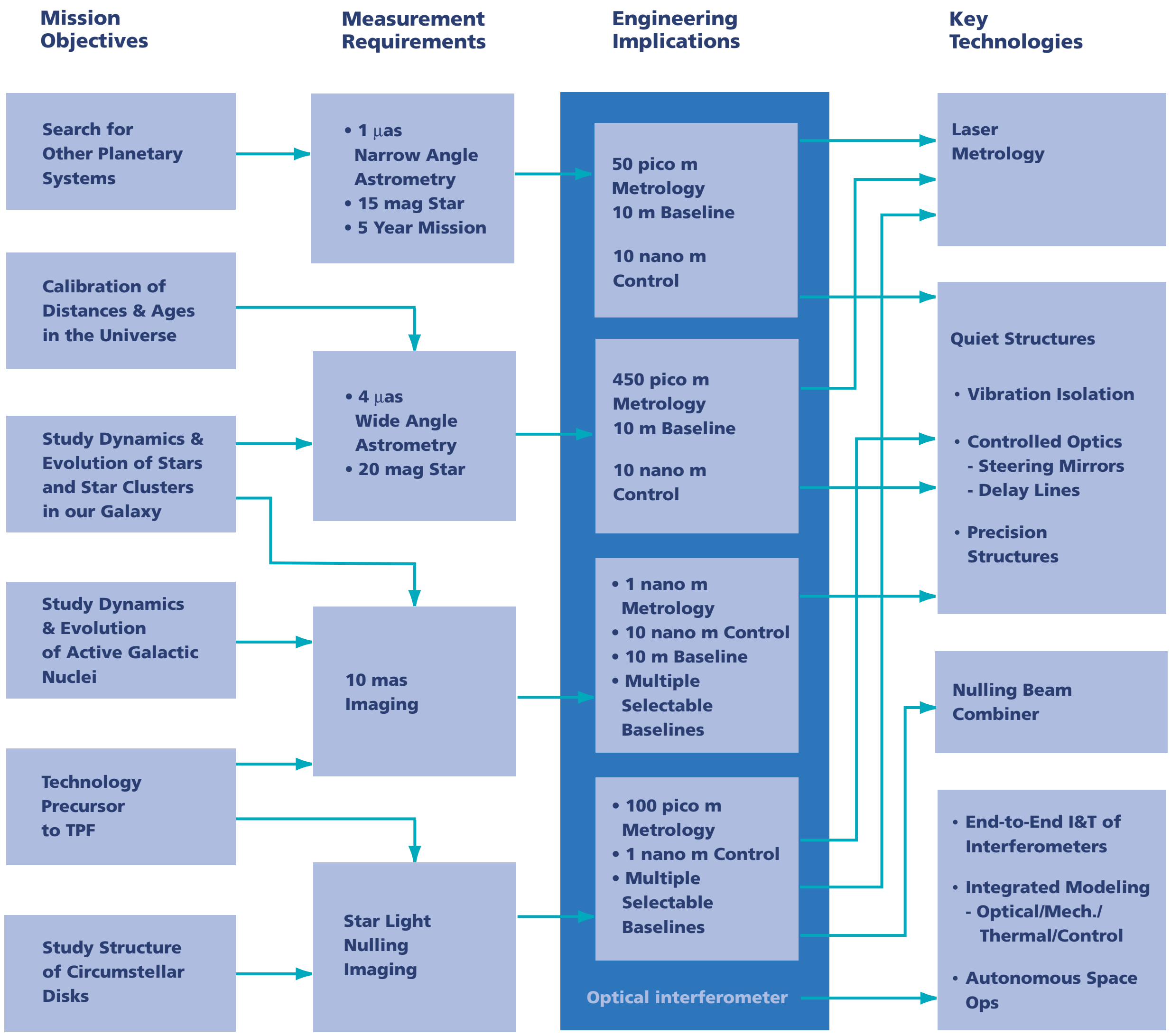
At the highest level, the enabling technologies for SIM can be grouped into two categories:

1-Nanometer-level control and stabilization of optical pathlength on a lightweight flexible structure

2-Subnanometer-level sensing of the relative positions of optical elements over separation distances >10 m

Control and Stabilization. The primary observable in an interferometer is the interference fringe resulting from combining the light beams from the two arms of the interferometer. The need for nanometer-level control and stabilization of the optical path is driven by the need to minimize pathlength fluctuations, which otherwise would blur the fringe. For astrometry and imaging, the required real-time pathlength control is $\lambda/50$ — for SIM, that translates to 0.5 μm/50 = 10 nm.

This requirement is more stringent when the interferometer is used in the nulling mode; the pathlength control requirement is then about $(\lambda/2\pi)$*(sqrt(null depth)). For the SIM follow-on mission, Terrestrial Planet Finder, where λ is nominally 10 μm and the required null depth is 10^{-6}, the pathlength must be controlled to ~1 nm. Because SIM is to demonstrate nulling technology prior to TPF, this same 1-nm pathlength control is also levied on SIM. At the SIM wavelength of 0.5 μm, the result is a nulling depth of approximately 10^{-4}.



Sensing. The need to measure pathlengths to subnanometer levels is directly tied to the desired astrometric accuracy. For SIM, the required accuracy is 4 µas for global astrometry and 1 µas over a narrower angle for planet detection. With SIM's 10-m baseline, the 1-µas (5-picoradian) requirement necessitates measurements of the baseline positions to 50 pm.

Technology Development Approach

The fundamental approach for SIM technology development is one of rapid prototyping of critical hardware (delay

Key technologies for SIM can be traced to the measurements required to satisfy mission objectives.

line, beam combiner, metrology hardware, etc.) and software (real-time control), followed by integration into technology testbeds. Using these testbeds, critical interfaces can be validated, system-level performance demonstrated, and integration and test procedures developed and verified.

Three major ground testbeds are planned: the SIM System Testbed (STB), the Microarcsecond Metrology (MAM) Testbed, and the Palomar Testbed Interferometer (PTI).

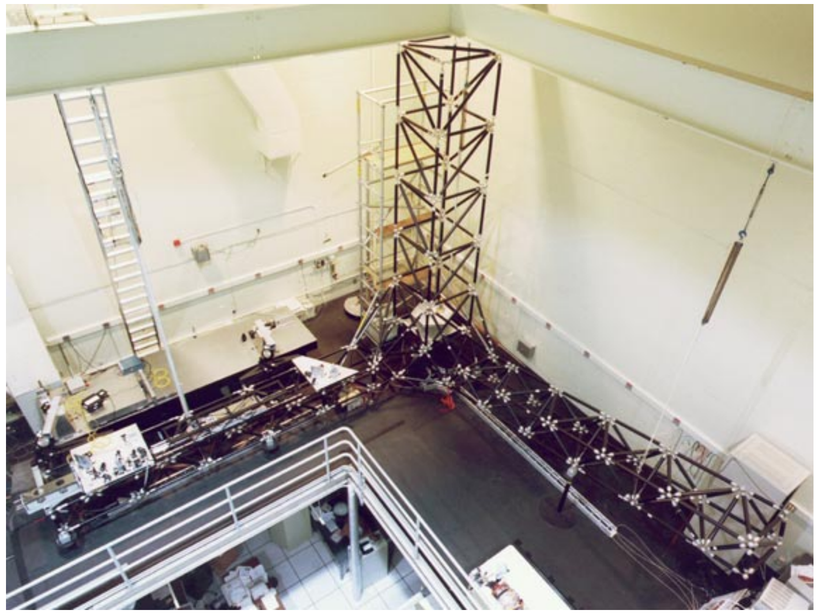
SIM System Testbed

The STB — an evolutionary series comprising two testbeds — is a full-scale, near-full-complexity testbed operated in air and intended to demonstrate nanometer-level pathlength control. The first in the series, STB-1, was started in 1991 and finished in 1994, when "first fringes" were acquired. It is a single-baseline interferometer built on a flexible structure using breadboard hardware components. The second in the series, STB-3, is a three-baseline interferometer (similar to SIM itself) with the goal to have its operational complexity approach that of the SIM flight instrument.

Two metrics have been tracked over time to monitor STB-1 progress — fringe stability in the presence of the laboratory ambient vibration environment, and fringe stability versus emulated spacecraft reaction wheel disturbances (expected to be the dominant on-orbit disturbance source). The current (fall 1998) performance, as measured by each metric, is below 5 nm RMS. This already exceeds the 10-nm requirement for astrometry, and within reach of the 1-nm control needed for nulling.

Microarcsecond Metrology Testbed

The measurement of distance changes at the <50-pm level requires a vigorous technology program to develop lasers, modulators, and metrology gauges with ultrahigh precision and thermal stability. The feasibility of picometer metrology has been established in small-scale vacuum experiments using multiple laser gauges for consistency measurements. These experiments have yielded a precision of hundreds of picometers to date and are targeting the requisite 50 pm by the end of 1999. However, demonstrating SIM's microarcsecond angular measurement capability requires arraying a set of these 1-D metrology gauges in a system-level emulation of SIM



astrometry. This will be done in the MAM testbed, which will demonstrate measurement of a point source (an artificial star) position to the microarcsecond level. A 1.8-m-baseline interferometer (one-fifth scale) will be placed in a 3-m by 13-m vacuum chamber to observe the artificial star. The positions of the star and the interferometer will be monitored by an external metrology system that allows calibration of the star position measured by the interferometer. Initial MAM operation is planned for late 1999.

The SIM technology development approach is one of fast prototyping of hardware, such as the optical delay line (above left), and control software; then testing these in the system-level testbeds STB (above) in air and MAM (below) in a vacuum tank .

Palomar Testbed Interferometer

The PTI is an operational interferometer used as an engineering testbed but capable of doing modest science. The real-time control software developed for PTI has been extensively used in developing the software for the SIM System Testbed, which is in turn the incubator for SIM flight software.

Ground-Based Interferometer Observatories

Ground-based interferometers are invaluable testbeds for space-based systems, not only from a hardware perspective, but also with a view toward operations and scientific productivity. Members of the JPL SIM team have built and operated a series of ground interferometers over a period of nearly 20 years. These have pioneered advances in interferometer architecture, algorithms, performance, automation, and scientific productivity that are directly applicable to SIM.

Palomar Testbed Interferometer

Development of PTI began in December 1992. The site at Palomar Mountain was available for occupancy in May 1995, and first fringes were obtained three months later, in July 1995. The instrument recently attained its performance goal of sub-50-μas narrow-angle astrometry over a single observation time on the order of hours. Testing of multinight astrometric measurement stability is currently under way.

PTI has a 110-m baseline, employing 50-cm siderostats with 40-cm telescopes. It is a dual-star system, using a bright target star to cophase the system in order to detect a faint astrometric reference star against which the astrometric perturbations of the bright target are measured. The architecture is fairly autonomous. As a demonstration of the type of autonomy necessary for the operation of space systems, PTI has been operated remotely from JPL, more than 160 km away.

The Palomar Testbed Interferometer is serving as an engineering and operational testbed for both the Keck Interferometer and SIM.

Development of the Keck Interferometer is taking place in parallel with SIM technology development, allowing synergistic development in a number of areas.

The Keck Interferometer

A development is currently under way to link into an interferometer the two 10-m Keck telescopes, located 85 m apart on the summit of Mauna Kea in Hawaii. Once developed, the Keck Interferometer will become one of the world's premier infrared interferometry facilities. The two-element Keck Interferometer will come on line by late 2000. Development is also under way to add four 1.5-m "outrigger" telescopes at the same site for a more capable interferometric array. The complete array is expected to be on line in late 2002. The array will be capable of 3 mas imaging at 2 µm. The four outriggers will be capable of 20 µas astrometry.

Development of the Keck Interferometer is taking place largely in parallel with the development of SIM technology at JPL. This has enabled synergistic work in at least two important areas: real-time software and starlight nulling. Keck and SIM will both make use of the same core software being developed by the interferometry technology program now under way at JPL. This should benefit SIM because another operational system will be the first to check out and run the software.

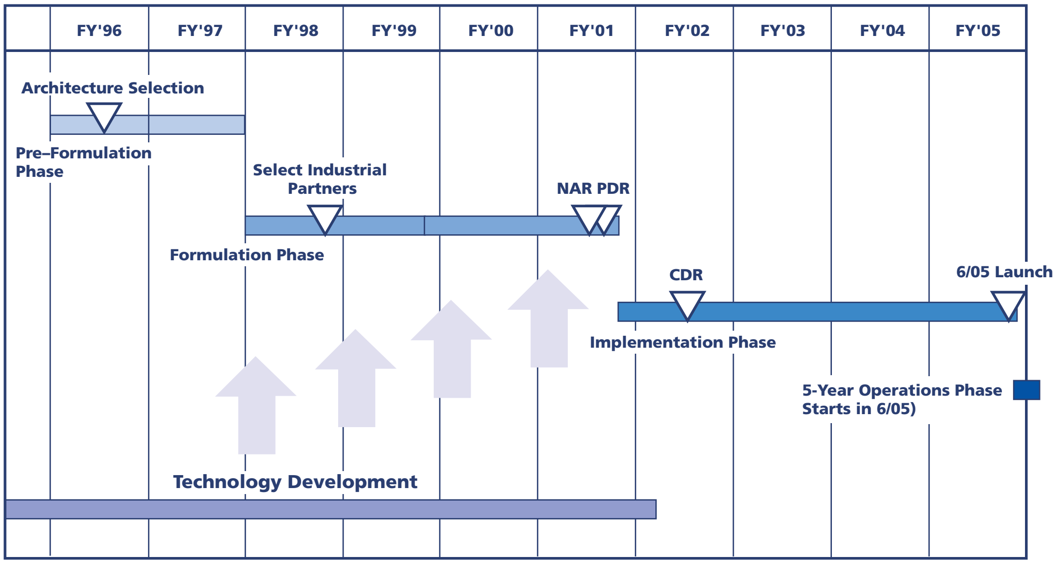
SIM

Programmatics

Schedule

SIM entered its formulation phase in October 1997 to develop the critical technologies, firm up science and engineering requirements, explore the mission trade space, and perform the preliminary design. The formulation phase ends in a Preliminary Design Review (PDR) and a Nonadvocate Review (NAR) to determine if the mission is ready to proceed to the Implementation Phase. During the implementation phase, detailed design will be undertaken and reviewed at a Critical Design Review (CDR). Fabrication, integration, test, and launch complete the implementation phase. SIM is scheduled to enter the development phase in mid to late 2001, launch in the second half of 2005, and operate on orbit for five years.

During the four-year formulation phase (1997–2001), the SIM team will develop key technologies, perform system trades, firm up the requirements, and arrive at the preliminary design. The subsequent 4-year implementation phase culminates in launch in mid-2005, followed by a 5-year operations period.



Development Cost

SIM's cost during the implementation phase is $480M in actual-year dollars. Additionally, during the formulation phase, approximately $120M will be spent on technology development, mission trades, and preliminary design.

The SIM Team

NASA has assigned the responsibility for the development of SIM to the Jet Propulsion Laboratory, California Institute of Technology. Two industry partners have been selected: Lockheed Martin Missiles and Space in Sunnyvale, California, and TRW Space and Electronics in Redondo Beach, California. While the three partners are assimilated into a single cohesive team, each has a major area of responsibility. JPL is the overall mission manager and leads in the interferometry initial design and technology development. Lockheed Martin is the interferometry partner and will build, integrate, and test the interferometer, with the support of JPL. TRW is the spacecraft partner and will provide the engineering subsystem and the 10-m “quiet” structure, which is the backbone of the instrument and serves as the interferometer baseline. TRW will provide integration and test of the instrument with the spacecraft, as well as launch-site operation.

The Infrared Processing and Analysis Center (IPAC) in Pasadena, California, has been designated the interferometry science center and will provide the initial data processing and archiving functions, first for the Keck Interferometer, and then for SIM.

SIM Quick Facts

Launch Date	Mid-2005
Launch Vehicle	Delta III Class
Orbit	Heliocentric Earth-trailing
Mission Life	5 years
Wavelength	0.4-0.9 µm

Global Astrometry

Single-Observation Accuracy	10 µas
End-of-Mission Accuracy	4 µas
Field of Regard	15 degrees
Number of Grid Stars	5,000

Narrow-Angle Astrometry

Accuracy	1 µas
Field of Regard	1 degree

Baseline	10 meters
Imaging Resolution	10 mas
Imaging Field of View	0.3 arcsec

Key Technology Requirements

Pathlength Stabilization for Astrometry	10 nm
Pathlength Stabilization for Nulling	1 nm
Pathlength Knowledge	0.05 nm
Starlight Nulling	10^{-4}

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